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IS : 9029 - 1978

*Indian Standard*

**METHODS OF TESTS FOR BATCH FURNACES  
WITH METALLIC HEATING RESISTORS**

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**INDIAN STANDARDS INSTITUTION**  
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**AMENDMENT NO. 1      JUNE 1981**  
**TO**  
**IS : 9029 - 1978   METHODS OF TESTS FOR**  
**BATCH FURNACES WITH METALLIC HEATING**  
**RESISTORS**

**Corrigenda**

( *Page 13, clause 3.17.1, last line* ) — Substitute '  $E_{ac} = E_a - E_o$  in Wh ' for '  $E_{ac} = E_a - E_a$  in Wh '.

[ *Page 20, clause A-3.1, equation (7)* ] — Substitute  
'  $U_1 = R_1 I_0 ( 1 - e^{-t/T_1} )$  ' for '  $U_1 = R_1 I_0 ( 1 - e^{-t/T_k} )$  '.

[ *Page 20, clause A-3.2, equation (9)* ] — Substitute

$$' F(t) = \frac{U(t)}{I_o} = \frac{U(t)}{i(t)} = \sum_{k=1}^{k=n} R_k ( 1 - e^{-t/T_k} ) ' \text{ for}$$

$$' F(t) = \frac{U(t)}{I_o} = \frac{U(t)}{i(t)} = \sum_{k=1}^{k=n} R_k ( 1 - e^{-t/T_k} ). '$$

( ETDC 61 )

# Indian Standard

## METHODS OF TESTS FOR BATCH FURNACES WITH METALLIC HEATING RESISTORS

Industrial Electroheating Equipment Sectional Committee, ETDC 61

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**IS : 9029 - 1978**

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## *Indian Standard*

# METHODS OF TESTS FOR BATCH FURNACES WITH METALLIC HEATING RESISTORS

### 0. FOREWORD

**0.1** This Indian Standard was adopted by the Indian Standards Institution on 14 December 1978, after the draft finalized by the Industrial Electroheating Equipment Sectional Committee had been approved by the Electrotechnical Division Council.

**0.2** This standard covers the testing conditions and methods to determine the essential parameters and technical data of indirectly heated industrial furnaces.

**0.3** In formulating this standard, considerable assistance has been derived from the following IEC Publications issued by the International Electrotechnical Commission:

IEC Publication 397 ( 1972 ) Test methods for batch furnaces with metallic heating resistors (*first edition*).

IEC Publication 397A ( 1975 ) Test methods for batch furnaces with metallic heating resistors, Sub-clause 5.14 : Determination of accumulated heat.

**0.4** In reporting the result of a test or analysis made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960\*.

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### 1. SCOPE

**1.1** This standard specifies methods of tests for industrial furnaces heated indirectly with metallic heating elements ( for example, for heat treatment, hot forming, etc ) in which the internal atmosphere is composed of air not intentionally modified.

This standard applies to batch chamber, bell, elevator, shaft, carriage, or to furnaces of any similar construction. These furnaces may be constructed either with or without forced air circulation.

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\*Rules for rounding off numerical values (*revised*).



Furnaces of low and very low voltage categories ( below 500 V ) are covered by this standard.

## **2. TERMINOLOGY**

**2.0** For the purpose of this standard, the following definitions shall apply.

**2.1 Indirect Resistance Electric Furnace** — Furnaces in which the heat evolved by the Joule effect in the heating elements is transferred to the material to be heated.

**2.2 Charge** — Total of materials to be heated at the same time in the furnace.

**2.3 Heating Element** — Electric conductor with ohmic resistance, connected to the source of electric energy, in which the electric energy is transformed to thermal energy by the Joule effect.

**2.4 Heating Assembly** — Assembly of heating elements controlled, regulated or switched jointly.

**2.5 Furnace Temperature  $\theta_1$**  — The temperature, in degrees Celsius, at one or more specified points in the heated space of the furnace.

**2.6 Rated Maximum Furnace Temperature  $\theta_n$**  — The rated operating temperature, in degrees Celsius, in normal service of the furnace for which the furnace is designed. It is indicated on the nameplate of the furnace.

**2.7 External Surface Temperature of the Furnace  $\theta_s$**  — The temperature, in degrees Celsius, measured at one or more determined points on the outer surface of the furnace.

**2.8 Ambient Temperature  $\theta_a$**  — The temperature, in degrees Celsius, of air surrounding the furnace at a point where thermal radiation and natural convection from the furnace do not exert any influence.

**2.9 Reference Ambient Temperature  $\theta_r$**  — Ambient temperature, in degrees Celsius, to which all furnace characteristic data are referred.

**2.10 Temperature-Time Variation** — The temperature, in degrees Celsius, variation at a given point in the furnace plotted against time.

**2.11 Surface Temperature of the Furnace at Thermal Steady-State  $\theta_{s0}$**  — The temperature, in degrees Celsius, reached at thermal steady-state at a predetermined point on the external surface of the furnace.

**2.12 Rated Furnace Voltage  $U_n$**  — The voltage, in volts, for which the furnace is designed. It is given on the nameplate.

**2.13 Furnace Power  $P$**  — Power, in kilowatt, consumed by the heating elements of the furnace at a given time.

**2.14 Furnace Rated Power  $P_n$**  — Power, in kilowatt, consumption of the furnace at the rated furnace voltage, rated current, rated frequency and rated temperature.

**2.15 Mean No-Load Input Loss  $P_o$**  — The energy loss in kWh in unit time ( in hours ) at the rated temperature of the empty furnace in normal operating conditions in thermal steady-state. In this case, the power demand of auxiliary devices, determined for the heating assembly ( for example, fan ), should be added to the furnace rated power.

**2.16 Electric Power Input of Furnace Switched on in Cold State  $P_i$**  — The input power, in kilowatt, at the moment of switching on the cold furnace.

**2.17 Heating-up Time  $t_p$**  — The time, in hours, necessary to heat a dried, empty, closed furnace from reference ambient temperature at rated voltage so that the temperature measuring equipment indicates the rated furnace temperature.

**2.18 Connected Load  $P_{tot}$**  — Maximum furnace power input measured at rated voltage.

**2.19 Time for Attainment of Thermal Steady-State  $t_{th}$**  — The time, in minutes and hours, between switching on the furnace in the cold state and attainment of thermal steady-state.

**2.20 Thermal Steady-State of Furnace** — The thermal condition when all energy input is used to cover heat losses.

**2.21 Cold Furnace Condition** — The thermal condition in which the temperature of the assembly of constructional elements of the furnace equals the ambient temperature.

**2.22 Hot Furnace Condition** — The thermal condition when the rated temperature is reached.

**2.23 Energy Condition  $E$**  — The quantity of energy, in kilowatt-hour, consumed by the furnace during a given time without charge.

**2.24 Heating-Up Energy Consumption  $E_A$**  — The quantity of energy, in kilowatt-hour, absorbed by the empty furnace between switching on the cold furnace and attainment of the thermal steady-state without charge.

**2.25 Leakage Current** — Leakage current is the current which in normal operation flows from live parts of the installation or apparatus through or

over the functional insulation to conducting parts not forming part of the working circuit when these last-mentioned parts are electrically connected to the middle point of the power system or to a directly earthed point of the network.

### **3. TESTS**

**3.1 List of Tests** — The following tests are to be carried out for the assessment of the electro-heating equipment containing a furnace:

- a) Electric breakdown test of furnace insulation ( *see 3.4* );
- b) Measurement of power input of furnace switched on in cold-state ( *see 3.5* );
- c) Furnace temperature measurement ( *see 3.6* );
- d) Temperature measurement at the external surface of furnace ( *see 3.7* );
- e) Total energy consumption measurement ( *see 3.8* );
- f) Rated heating input measurement ( *see 3.9* );
- g) Heating-up time measurement ( *see 3.10* );
- h) Mean no-load loss power determination ( *see 3.11* );
- j) Determination of time necessary to reach the thermal steady-state ( *see 3.12* );
- k) Temperature measurement of accessible furnace parts ( *see 3.13* );
- m) Determination of rated temperature change during the control cycle ( *see 3.14* );
- n) Leakage current measurement ( *see 3.15* );
- p) Determination of furnace temperature variation during the cooling period ( *see 3.16* ); and
- q) Determination of accumulated heat ( *see 3.17* ).

**3.2 General Conditions of Test Performance** — *See IS : 9021-1978\**.

#### **3.3 Particular Conditions of Tests**

- a) Tests according to **3.1** are realized on a furnace without charge;
- b) Tests with charge are to be agreed upon between the manufacturer and the user;
- c) When the furnace has a mechanical or electric regulation, appropriate test methods should be agreed upon between the manufacturer and the user.

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\*General test conditions for industrial electro-heating equipment.

### 3.4 Electric Breakdown Test of Furnace Insulation

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NOTE — Tests to be performed are under consideration.

**3.5 Measurement of the Power Input of Furnace Switched on in Cold-State  $P_f$**  — The power of a furnace switched on in cold-state  $P_f$  is measured by means of wattmeters; this power corresponds to the maximum value likely to be encountered in operation. In case wattmeters cannot be used, the power input can be determined approximately from current measurement at constant voltage when the circuit may be assumed to have ohmic resistance only.

NOTE — In case the connected load ( $P_{tot}$ ) exceeds the power of furnace switched on in cold-state, the method of measuring this power should be agreed upon between the manufacturer and the user.

**3.6 Furnace Temperature Measurement  $\theta_f$**  — The furnace temperature measurement inside the furnace shall be made at the place ( or places ) according to either preliminary agreement between manufacturer and user, or in accordance with the diagram of temperature distribution, given by the manufacturer.

The temperature variations are measured using a recording instrument or reading the values of temperature on an indicating instrument at regular time intervals of not longer than 1 hour. When the furnace temperature is close to the required one, or close to the rated temperature, the time interval of readout shall be reduced so as to allow an accurate determination of the moment of reaching the required temperature for the first time. The intervals should be not longer than 1 hour or another value agreed upon between the manufacturer and the user.

**3.7 Temperature Measurement at the External Surface of Furnace  $\theta_s$**  — The measurement is made at not less than three points, those being the points at which the highest and the lowest temperatures are expected, and a point in the centre of the side wall of the furnace. The measurement is performed at regular intervals until the temperature reaches a steady value. The time intervals should not be longer than 1 hour or another value agreed upon between the manufacturer and the user.

**3.8 Total Energy Consumption Measurement  $E_A$**  — The measurement is made by means of an electric energy meter, values being readout at regular time intervals until the temperature corresponding to that of the steady-state is reached. Measurements shall be made during a period not exceeding 0.5 hour.

**3.9 Rated Heating Input Measurement  $P_n$**  — The measurement is made by means of a wattmeter ( wattmeters ) or any other analogous device agreed upon by the manufacturer and the user at a temperature

fixed by these parties. This temperature is such that the measurement is made outside periods of automatic temperature and power regulation.

NOTE 1 — In case this measurement cannot be made by means of a wattmeter, the rated input power may be determined from the consumed energy as follows:

The energy consumption should be measured during a given time interval on the attainment of the thermal steady-state.

The consumed energy is read at regular time intervals. The last interval before readout of the rated temperature is used for rated input calculation.

If  $\Delta t$  is the interval during which energy consumption is measured and  $E$  is the consumed energy in this interval, then the rated input  $P_n$  equals:

$$P_n = \frac{E}{\Delta t} \text{ in kW}$$

NOTE 2 — If, during the power measurement, the voltage across terminals differs from the rated voltage, the reduction to rated voltage shall be made using the formula:

$$P_n = P'_n \left( \frac{U_n}{U} \right)^2$$

where

$P_n$  = rated input at rated voltage in kW,

$P'_n$  = input measured at the voltage other than rated in kW,

$U_n$  = rated furnace voltage in volts, and

$U$  = voltage across terminals at the moment of input measurement in volts.

The rated input is given for the whole furnace, unless otherwise agreed between the manufacturer and the user.

**3.10 Heating-Up Time Measurement  $t_p$**  — The time interval between switching-on the cold furnace connected to the rated voltage and the attainment of rated temperature is measured. Should the furnace have more than one heating assembly, the heating-up time is that necessary for the whole furnace ( all heating assemblies in operation ) to reach the rated temperature for the first time.

**3.11 Mean No-Load Loss Power Determination  $P_0$**  — For the determination of no-load losses, it is necessary to make sure that the thermal steady-state is reached at the rated temperature. The energy consumption is measured according to 3.8. If the energy consumption is  $E_1$  in the time interval  $\Delta t_1$ ,  $E_2$  in the time interval  $\Delta t_2$ , and  $E_3$  in the time interval  $\Delta t_3$ , then its mean value is:

$$E_{m1} = \frac{E_1 + E_2 + E_3}{3} \text{ in kWh}$$

The time intervals shall be of equal duration ( at least 30 minutes ):

$$\Delta t_1 = \Delta t_2 = \Delta t_3 = \Delta t_n = \Delta t \text{ ( hours )}$$

If  $E_{\max}$  or  $E_{\min}$  respectively is the highest or lowest value of  $E_1$ ,  $E_2$  and  $E_3$ , then

$$\Delta_1 = 100 \frac{E_{\max} - E_{\min}}{E_{m1}} \text{ percent}$$

Similarly, the mean value from  $E_2$ ,  $E_3$  and  $E_4$  is:

$$E_{m2} = \frac{E_2 + E_3 + E_4}{3} \text{ in kWh}$$

and

$$\Delta_2 = 100 \frac{E_{\max} - E_{\min}}{E_{m2}} \text{ percent}$$

where  $E_{\max}$  and  $E_{\min}$  are extreme values of  $E_2$ ,  $E_3$  and  $E_4$ .

Similar calculations are repeated until the successive values  $\Delta_n$  and  $\Delta_{n-1}$  equal to or less than 3 percent are reached:

$$\Delta_n \leq 3 \text{ percent}$$

$$\Delta_{n-1} \leq 3 \text{ percent}$$

The 3 percent value was derived from the practical measurements, and is a recommended value.

The loss power input in thermal steady-state is then:

$$P_o = \frac{E_{mn}}{\Delta t} \text{ in kW}$$

where  $E_{mn}$  = mean value corresponding to the last measurement.

**3.12 Determination of Time Necessary to Reach the Thermal Steady-State  $t_h$**  — The time of reaching the thermal steady-state is found using the procedure described in 3.11.

This time is the interval between the time of switching-on the furnace and the time of the last measurement of consumed energy during the determination of mean no-load loss power.

**3.13 Temperature Measurement of Accessible Furnace Parts** — The temperature is measured on all parts that might be touched or handled by the operators during normal furnace operation.

This measurement is performed in thermal steady-state at the rated furnace temperature attained.

**3.14 Determination of Rated Temperature Change During the Control Cycle** — The performance of the temperature control device or devices is determined in thermal steady-state of the furnace.

The variation of the temperature inside the furnace between two control cycles of temperature control devices is measured according to 3.6 in the case of step control, or the deviation between the maximum and minimum temperature is measured at an interval of at least 30 minutes in the case of continuous control.

The variation of  $\Delta\theta_1$  of the internal temperature is measured. It is recommended to make several measurements of the quantity  $\Delta\theta_1$ .

**3.15 Leakage Current Measurement** — Leakage current is measured when the furnace has reached the rated temperature and is in a steady-state.

The leakage current is measured between any mains pole and accessible metallic parts.

The wiring diagram for single-phase furnaces with rated voltage not exceeding 240 V is given in Fig. 1, and for three-phase furnaces in Fig. 2.

The resistance of the measuring circuit between the framework and the mains terminals is  $2\,000 \pm 100$  ohms. For single-phase furnaces with rated voltage not exceeding 240 V, the leakage current is measured setting the switch successively in positions 1 and 2 ( see Fig. 1 ).

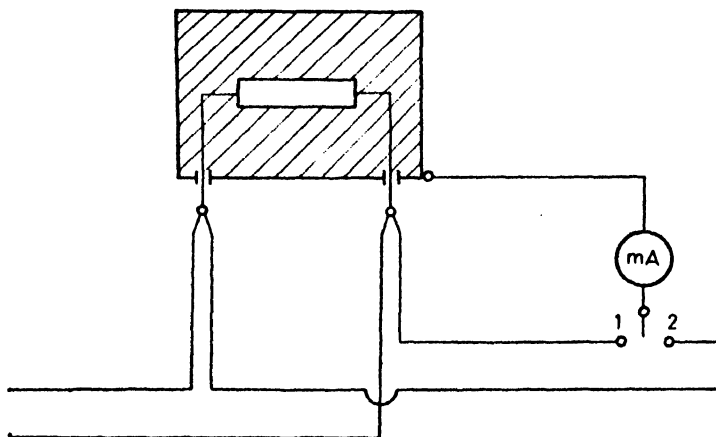
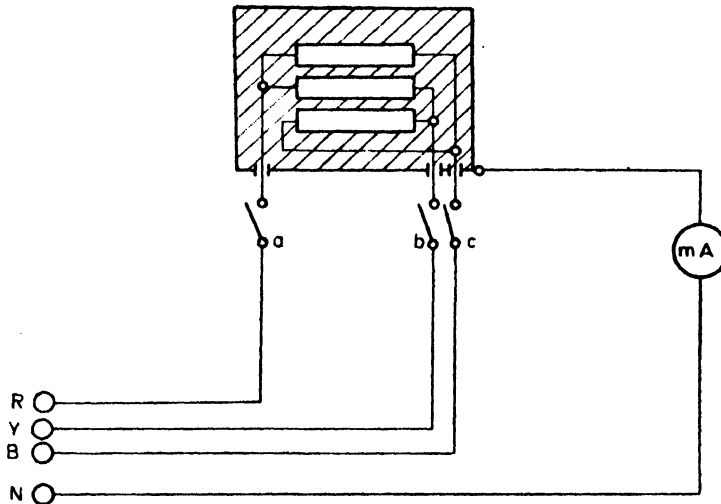


FIG. 1 WIRING DIAGRAM FOR LEAKAGE CURRENT MEASUREMENT IN HOT-STATE IN A SINGLE-PHASE FURNACE



**FIG. 2 WIRING DIAGRAM FOR LEAKAGE CURRENT MEASUREMENT IN HOT-STATE IN A THREE-PHASE FURNACE**

For all other types of furnaces, the leakage current is measured with contacts *a*, *b* and *c* closed ( *see* Fig. 2 ). In three-phase furnaces not connectable as single-phase ones, measurements must be repeated opening in turn each switch *a*, *b* and *c* leaving the other two closed; in single-phase furnaces, the measurements are repeated with one switch open.

It is recommended to supply the furnace through an isolation transformer or if it is not possible, to insulate the furnace from earth.

If the measurement circuits according to Fig. 1 and 2 may not be used, the differential residual current method ( *see* Fig. 3 ) may be adapted for the measurement of leakage currents.

For three-phase furnaces, the most unfavourable case should be measured as stated above.

The measurement shall be made under conditions specified by safety regulations,



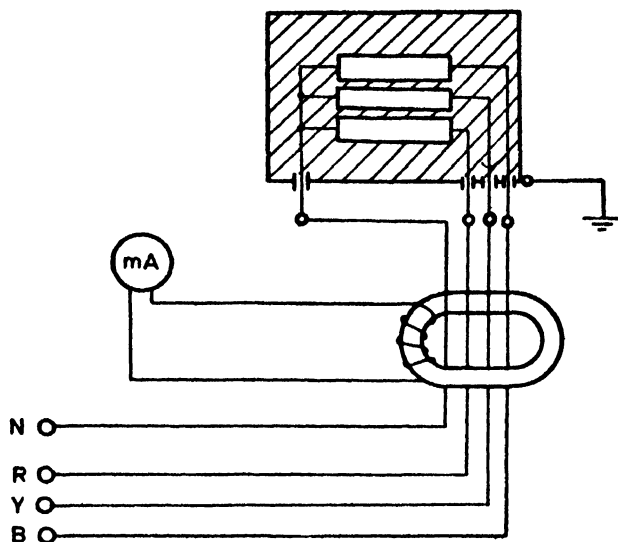


FIG. 3 WIRING DIAGRAM FOR LEAKAGE CURRENT MEASUREMENT  
USING THE DIFFERENTIAL CURRENT METHOD

**3.16 Determination of Furnace Temperature Variation During the Cooling Period** — The cooling curve may be required. When the furnace reaches the thermal steady-state, it is switched off and the furnace temperature is measured at the point(s) specified in 3.6. The furnace temperature curve is read from the value  $\theta_n$  (rated temperature) to the value  $\theta$  agreed between the manufacturer and the user.

**3.17 Determination of Accumulated Heat** — The accumulated heat of a furnace in steady-state may be determined by different methods. This standard describes two such methods; one called the direct and the other the indirect method. The direct method is the basic method. The indirect method, also called the Beuken method, because of its simplicity, is particularly convenient for industrial measurements. The method applied should be stated with the result.

**3.17.1 Direct Method (Classical Method)** — The accumulated heat  $E_{ao}$  of a furnace is determined by calculating the difference between the thermal energy  $E_a$  supplied during heating of the furnace from cold-state to steady-state and the energy  $E_o$  transmitted by the furnace to the ambient medium during its heating period.

On condition that there is a direct proportionality between temperature rise at the external surface of the furnace and the heat loss from this surface,  $E_o$  can be calculated from the following expression:

$$E_o = \frac{P_o}{\theta_{s,n} - \theta_a} \sum_{k=1}^n \left[ \frac{\theta_s (k-1) - \theta_{s,k}}{2} - \theta_a \right] \Delta t_k \quad \dots (1)$$

where

$P_o$  = no-load losses in steady-state in watt;

$\theta_{s,n}$  = superficial temperature of furnace in steady-state in °C;

$\theta_a$  = ambient temperature in °C;

$\theta_{s,k}$  = superficial temperature of furnace, in °C after the interval  $\Delta t_k$ , measured in accordance with 3.7 in °C; and

$\Delta t_k$  = time interval between two successive measurements in h.

The accumulated heat is hence:

$$E_{a0} = E_a - E_s \text{ in Wh}$$

**3.17.2 Indirect Method (Beuken Method)** — When cooling a furnace from a given steady-state down to the ambient temperature, the temperature variation inside the furnace is expressed by the following:

$$\theta_1(t) - \theta_a = \sum_{k=1}^n \theta_k e^{-t/T_k} \quad \dots (2)$$

where

$\theta_1$  = temperature in °C inside the furnace,

$\theta_k$  = temperature in °C determined according to Fig. 5, and

$T_k$  = time constant in h determined from Fig. 5.

This can also be expressed by:

$$\theta_1(t) - \theta_a = \theta_1 e^{-t/T_1} + \theta_2 e^{-t/T_2} + \dots + \theta_n e^{-t/T_n} \quad \dots (3)$$

When the furnace can be considered as a linear thermal system, the accumulated heat in steady-state  $E_{a0}$  is given by (see Appendix A):

$$E_{a0} = P_o \sum_{k=1}^n T_k = P_o (T_1 + T_2 + \dots + T_n) \quad \dots (4)$$

where

$P_o$  = no-load losses in steady-state, equivalent at a given moment to the heating power in steady-state in W,

$E_{ao}$  = accumulated heat in steady-state in Wh, and  
 $T_1 \dots T_n$  = time constants in h.

Equation (4) may be rewritten in the form:

$$E_{ao} = P_o (\theta_{i,o} - \theta_a) \frac{\sum_{k=1}^n T_k}{\sum_{k=1}^n \theta_k} \quad \dots (5)$$

where  $\theta_{i,o} = \theta_n$  = furnace temperature before heating was interrupted  
 and  $\theta_a$  = ambient temperature.

As a first approximation, if account is only taken of term  $k = 1$  having the highest time constant, the above expression can be reduced to:

$$E_{ao} = P_o (\theta_{i,o} - \theta_a) T_1 / \theta_1 \quad \dots (6)$$

The quantities  $\theta_{i,o}$ ,  $\theta_a$  and  $P_o$  are determined from measurements, while quantities  $T_1$  and  $\theta_1$  are derived from the temperature curve established during cooling (see Fig. 4) or by means of an adequate computer programme based on the same temperatures recorded during cooling.

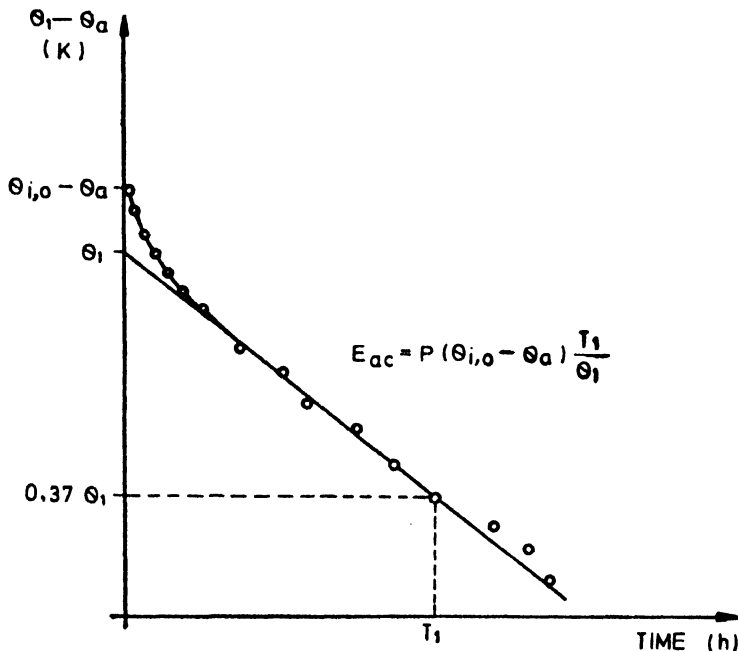


FIG. 4 TYPICAL TEMPERATURE CURVE PLOTTED DURING COOLING

**Practical Example** — The furnace is brought to steady-state at its normal utilization temperature and the average heating power during 1 h is measured ( read off on a watt-hour meter divided by the measuring time ). It should be checked whether the thermal steady-state has been really reached. The difference between two successive measurements should, if possible, not exceed 3 percent. The supply is then cut off and the temperature inside the furnace is recorded during cooling. The temperature inside the furnace is measured in reference to the ambient temperature which is measured by means of a globe pyrometer at a distance of 1 m from the furnace.

If the temperature inside the furnace is measured by means of thermocouples it suffices to use two identical thermocouples connected in opposition. The result  $(\theta_1 - \theta_a)$  is referred to the initial temperature difference  $(\theta_0 - \theta_a)$  and plotted on a semi-logarithmic diagram ( see Fig. 5 and 6 ).

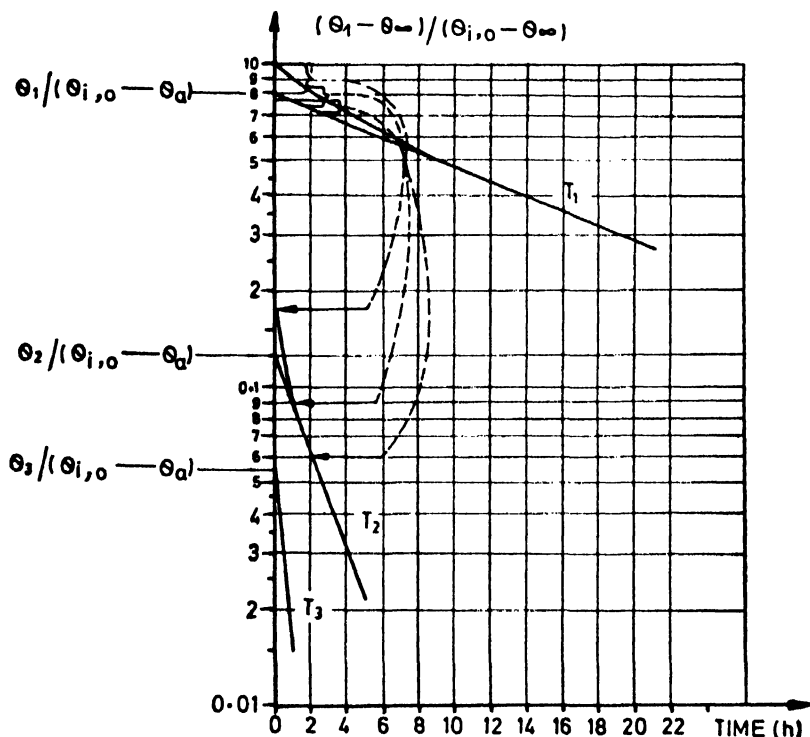


FIG. 5 COOLING CURVE STARTING FROM TEMPERATURE INSIDE THE FURNACE OF 602°C

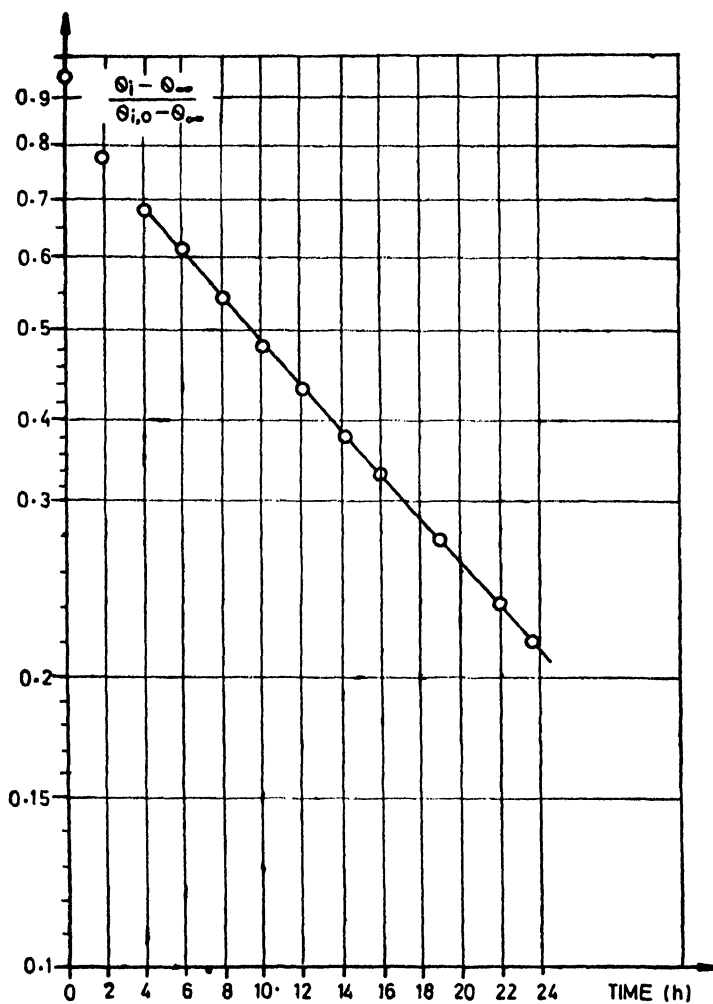


FIG. 6 COOLING CURVE STARTING FROM TEMPERATURE INSIDE THE FURNACE OF 1024°C

The linear zone allows for calculating  $T_1$  and the intersection with the axis of ordinates gives  $\theta_1/(\theta_{1,0} - \theta_a)$ . The deviation between the recorded cooling curve and the extrapolation up to the axis of ordinates of the last section being a straight line, is next plotted on a semi-logarithmic diagram, enabling  $T_2$  and  $\theta_2/(\theta_{1,0} - \theta_a)$  to be determined. The difference between the recorded curve and the improved approximation is again plotted on a diagram, therefore enabling  $T_3$  and  $\theta_3/(\theta_{1,0} - \theta_a)$ , etc, to be found.

Different parameters, derived in this way in the example given, may be listed in Table 1 for two initial temperatures of the same furnace.

TABLE 1 PARAMETERS

	SYMBOLS	UNITS	VALUE	VALUE
Initial temperature	$\theta_{1,0}$	°C	602*	1 024*
Final temperature = ambient temperature	$\theta_{\infty} = \theta_a$	°C	24	24
Temperature difference	$\Delta\theta = \theta_{1,0} - \theta_a$	K	578	1 000
Heating power (initial-final)	$\Delta P$	kW	1.497	3.00
Stationary thermal resistance	$R = \frac{\Delta\theta}{\Delta P}$	K/kW	386	333
Time constants	$T_1$	h	18.15	19.9
	$T_2$	h	2.85	2.8
	$T_3$	h	0.45	0.3
Relative amplitudes	$\theta_1/(\theta_{1,0} - \theta_a)$	percent	83.5	81.5
	$\theta_2/(\theta_{1,0} - \theta_a)$	percent	8.6	13.0
	$\theta_3/(\theta_{1,0} - \theta_a)$	percent	7.9	5.5
Accumulated heat in steady-state	$E_{ac}$	kWh	32.1	69
Accumulated heat (approximate formula) determined by the indirect method	$E_{ac}$	kWh	32.5	73.2
Accumulated heat determined according to the direct method during heating	$E_{ac}$	kWh	40	69.4
Accumulated heat determined according to the direct method during cooling	$E_{ac}$	kWh	31.6 to 33.3	56

\*The cooling curve starting from a temperature inside the furnace of 602°C is given in Fig. 5, and that starting from 1 024°C, in Fig. 6.

## APPENDIX A

( Clause 3.17.2 )

## ANALOGOUS ELECTRIC MODEL OF ACCUMULATED HEAT

## A-1. FURNACE TEMPERATURE

**A-1.1** During cooling when the heating power becomes zero, the temperature of the furnace wall at any arbitrary point varies according to the expression:

$$\theta_1(t) - \theta_a = \sum_{k=1}^{k=n} \theta_k e^{-t/T_k} \quad \dots (1)$$

**A-1.2** On the contrary, during heating of the furnace supplied with a constant power  $P_t = P_o$ , the temperature of the furnace wall at any arbitrary point varies in the following manner:

$$\theta_1(t) - \theta_a = \sum_{k=1}^{k=n} \theta_k (1 - e^{-t/T_k}) \quad \dots (2)$$

## A-2. TRANSFER FUNCTION OF THE FURNACE

**A-2.1** The relation between the cause ( supply power ) and the consequence ( temperature rise ), in the case of heating of a furnace, is determined by the transfer function of the system ( furnace ):

$$\frac{\sum_{k=1}^{k=n} \theta_k (1 - e^{-t/T_k})}{P_o} = \frac{\theta_1(t) - \theta_a}{P(t)} = F(t) \quad \dots (3)$$

**A-2.2** A thermal system of this kind can be studied by means of an analogous electric circuit having a transfer function  $F(t)$  ( see Fig. 7 ).

**A-2.3** Taking into account the known analogy between temperature and voltage and between the heat flux and electric current, the transfer function will equal the ratio of voltage and current functions:

$$\frac{U(t)}{i(t)} = F(t) \quad \dots (4)$$

**A-2.4** It is immediately apparent that an RC network will meet these requirements, as for such a network the variation of voltages and currents with time is exponential.

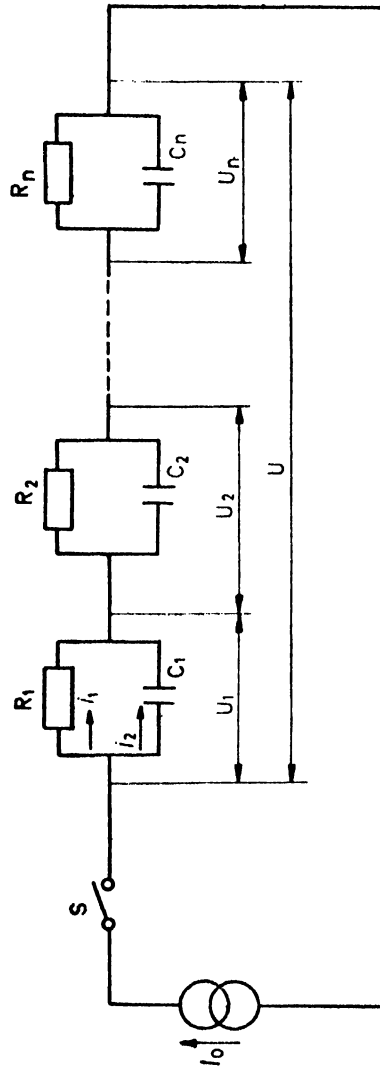


FIG. 7 ANALOGOUS ELECTRIC MODEL OF ACCUMULATED HEAT



### A-3. SOLUTION OF THE TRANSFER FUNCTION

**A-3.1** A possible solution is given in Fig. 7. The circuit is supplied by a source of constant current  $I_0$  and, after the loop is closed, the expression for the first link becomes:

$$I_0 = i_1 + i_2 \quad \dots (5)$$

and 
$$U_1 = \frac{1}{C_1} \int i_2 dt \text{ hence } i_2 = C_1 \frac{dU_1}{dt}$$

$$U_1 = R_1 i_1 \text{ hence } i_1 = \frac{U_1}{R_1}$$

and

$$I_0 R_1 = U_1 + R_1 C_1 \frac{dU_1}{dt} = U_1 + T_1 \frac{dU_1}{dt} \quad \dots (6)$$

when  $T_1 = R_1 C_1$

The solution of this equation is:

$$U_1 = R_1 I_0 (1 - e^{-t/T_1}) \quad \dots (7)$$

**A-3.2** An identical solution is valid for other RC nodes. Thus, the expression for the total voltage  $U$  will read:

$$U(t) = \sum_{k=1}^{k=n} R_k I_0 (1 - e^{-t/T_k}) \quad \dots (8)$$

with

$$F(t) = \frac{U(t)}{I_0} = \frac{U(t)}{i(t)} \sum_{k=1}^{k=n} R_k (1 - e^{-t/T_k}) \quad \dots (9)$$

**A-3.2.1** Comparing formula (9) with formula (3) it may be concluded immediately that the network given in Fig. 7 can be considered as analogous to the furnace wall.

The analogous values are the following:

<i>Furnace</i>	<i>Electric Model</i>
$\theta_1(t)$	$U(t)$
$P(t) = P_0$	$i(t) = I_0$
$\frac{\theta_1}{P_0}$	$R_1$

**A-4. SOLUTION FOR THE HEAT ACCUMULATED IN FURNACE**

**A-4.1** On the other hand, the analogy of the heat accumulated in furnace walls during its heating to its steady-state temperature corresponds to the total charge of capacitors of the analogous electric circuit supplied by a source of current  $I_o$ , in steady-state.

**A-4.2** The latter quantity may easily be calculated. In fact:

$$\sum_{k=1}^{k=n} E_{k0} = \sum_{k=1}^{k=n} C_k U_k = \sum_{k=1}^{k=n} C_k R_k I_o \quad \dots \quad (10)$$

or

$$\sum_{k=1}^{k=n} E_{k0} = I_o \sum_{k=1}^{k=n} T_k \quad \dots \quad (11)$$

Thus, the expression for the heat accumulated in the furnace equals, by analogy:

$$E_{ao} = P_o \sum_{k=1}^{k=n} T_k \quad \dots \quad (12)$$

**A-4.3** This analogy, obtained when considering the furnace heating period, starting from the ambient temperature, is also valid when considering the cooling period, with the difference due to the electrical analogy that this period must be considered from the loop opening.

# INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

## Base Units

<i>Quantity</i>	<i>Unit</i>	<i>Symbol</i>
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

## Supplementary Units

<i>Quantity</i>	<i>Unit</i>	<i>Symbol</i>
Plane angle	radian	rad
Solid angle	steradian	sr

## Derived Units

<i>Quantity</i>	<i>Unit</i>	<i>Symbol</i>	<i>Conversion</i>
Force	newton	N	1 N = 0.101 972 kgf
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m <sup>2</sup>
Frequency	hertz	Hz	1 Hz = 1 c/s (s <sup>-1</sup> )
Electric conductance	siemens	S	1 S = 1 A/V
Pressure, stress	pascal	Pa	1 Pa = 1 N/m <sup>2</sup>